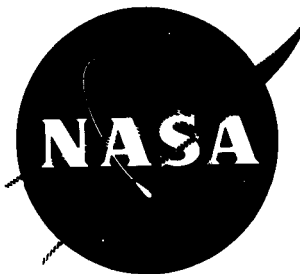


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by Maurice F. Baddour
Lewis Research Center
Cleveland, Ohio

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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The Centaur electrical system problems can be categorized into two areas, namely, the equipment and the power distribution interface.

The equipment problems are too extensive to be discussed at this conference, but an example will be used by showing how the inverter was removed from the critical list and made reliable enough to be flight qualified.

Later models of Atlas Centaur use two silver-zinc 100-ampere-hour batteries. The batteries have 19 cells each and are made by the Eagle-Picher Company to Centaur specifications. The batteries are contained in a plastic case which is in turn sealed in a stainless-steel container that has a pressure-relief valve. The batteries are placed on a fiber-glass heater-wire blanket which maintains temperature optimum by thermostat control throughout flight.

One battery is used for telemetry only, and the other battery is used mainly to drive the inverter and supply the balance of power to the guidance, autopilot, and fuel-utilization systems. It also acts as a bias supply and energizes relays for short periods of time.

The batteries are sealed in a stainless-steel container to prevent explosion in a vacuum environment and the container relief valve releases at approximately 25 psi to vent the gases. Problems were encountered with electrolyte leakage on the heater blanket, causing a short circuit to the outside case. This was solved by better activation procedure prior to launch, and by designing a vent valve on each cell which would vent gas without venting the electrolyte. There are two types of vent valves. One type is required for each cell of the battery in the steel case, and another is required on the stainless steel case itself. A new single plastic battery case design is approved to contain all cells which will improve reliability, increase strength and reduce weight.

Before going into the inverter, refer to Figure 1 which shows the battery electrical load profile for Atlas Centaur number 3 (AC-3). The solid line indicates the current drain on the main missile battery for the sequence of operation after launch. The dashed line indicates the telemetry battery current drain and shows a fairly constant load on the battery. Also, notice that for AC-3 the telemetry battery had a 250-ampere-hour capacity. For AC-4 and later models, both batteries are 100 ampere hour which is as physically small as can be obtained without affecting reliability. At launch, the main battery current-drain is

approximately 45 amperes and of that, about 37 amperes is delivered to the inverter. The balance of the current is distributed among the rest of the system to energize the different functions during or after launch.

The time scale in figure 1 is in seconds and the programmed flight is 1225.1 seconds. The mission requirement at present is approximately 16 minutes. There will be a time when it will reach 1 hour.

Before going into the inverter improvement program, a mechanical and electrical description of the inverter will be given. Figure 2 is a top view photograph of the inverter with the cover removed.

The inverter is approximately 10 by 16, by 6 inches, and weighs 37 pounds. The case is now white. It was found that the ability to dissipate heat in the vacuum environment of space is better with a white case than with a black case due to the spin cycle, which exposes the inverter to solar radiation. If the case were black, the heat absorbed from solar radiation would be greater than the reflectivity as a white body due to the internal heat generated. The inverter is in a closed case but is not hermetically sealed. The webs on the perimeter of the case do not have openings to the inside but are used to produce a chimney effect to encourage the flow of air before it reaches outer space. Their effect in a space environment is negligible.

The top of figure 2 shows, the circuit boards mounted in a plastic rack. Below the board rack are the commutating capacitors. In the middle of the inverter case is an aluminum partition that acts as a heat sink on which the silicon-controlled rectifiers (SCR's) are mounted. Below the heat sink is the output transformer with a Y-connected three-phase secondary wound on a single core. A fourth wire is used as neutral which is at ground potential. Tertiary windings in each phase are interconnected to produce harmonic cancellation. The secondary of the output transformer is fed to the output connector through the output filter and both can be seen in the lower left corner of the case. The input connector can be seen in the lower right corner of the case with the input filter mounted between the input and output connectors. The input charging chokes are the three inductors mounted on top of the output transformer.

The inverter is energized 12 hours prior to launch and has approximately 100 hours of running time on it, checking the missile out. The guidance system, which represents approximately 80 percent of the load, is energized at T-6 hours. From these facts it can be seen that the inverter has considerable ground operation prior to launch. Forced air cooling is always used on ground operation.

The fact that the inverter is not sealed has not produced an ionization problem in space. It was pointed out that corona effects would be produced, particularly, in the Van Allen Belt. Calculations

were made based upon the closest spaced terminals in the inverter. It was found that there was less than one microampere of current flow due to electron distribution in a vacuum due to molecular collision producing ions and electrons, and both producing random collision with the terminals.

A schematic of the inverter is shown in figure 3. The circuits enclosed by dashed lines represent circuit boards. Fortunately, the enclosed areas may also be used as a block diagram. Starting at the lower left-hand corner of figure 3 and moving up to the right, the blocks are self-identified as the overload circuit, the oscillator circuit, the countdown circuit and the core driver circuit which drives the shift register. The pulse output from the shift register is fed to a parallel-operated SCR inverter circuit which in turn is shunted by a magamp

There are three inverters timed 120 degrees apart, that produce the 3-phase, 115-volt, 400-cycle output across the secondary. The output is sensed both in voltage and current as feedback through a magamp regulator. The regulator feeds a pulse through the regulating SCR's whose pulse duration is a function of the current or voltage. If the regulators are considered as battery chargers, their operation is readily apparent. Excess energy is sensed by the magamp regulator, rectified, and is fed back into the battery line, between the battery and the overload circuit. This produces a back electromotive force (emf) which reduces the current requirement from the battery.

The input battery current must pass through the overload circuit (which is a misnomer). It is really a start-protection circuit as well. If the main SCR's are not commutated in perfect time coincidence with the resonant charge of the commutating capacitor, by the pulses derived from the shift core register, the overload circuit opens up the battery circuit and the process is repeated until time coincidence is achieved.

An important change in philosophy that has added to the reliability of the inverter is the elimination of the overload bypass circuit. This is the circuit in the schematic that would be energized by going through pin "B" of the input connector. It was normally energized by the missile changeover switch prior to launch. If the overload circuit is bypassed and a malfunction, a short circuit, or a decommutation occurs, all six of the main SCR's are destroyed within microseconds.

With the overload circuit in all the time, an overload current exceeding 400 percent develops sufficient voltage across R53 to fire CR40 which in turn extinguishes CR39 and thus opens up the battery input line. Once the circuit is open, the unijunction oscillator Q5 produces 5 pulses per second that fire the main overload SCR, CR39, to turn the system back on in case the overload condition has been cleared. This circuit will continue to sample the load condition indefinitely unless the battery is disconnected manually or the short circuit or overload has been removed to permit normal operation. The inverter has been

operated 24 hours with a dead short on the output with no degradation in performance when the short was removed. The reason the overload circuit became so important, prior to tests by Lewis Research Center, is that there was poor regulation in the oscillator circuit which made the inverter susceptible to noise and caused a lot of decommutation problems.

The crystal oscillator operates at 19.2 kilocycles with a decoupling stage into two unijunction countdown stages of 4 to 1 and 2 to 1 respectively. The 2400-pulse-per-second output from the countdown stages is used to trigger an SCR used as a core driver. The SCR in turn feeds a pulse through the shift register which consists of a series of six cores. Each core has four windings and is connected in series and parallel to produce a 60 degree phase shift every time a pulse is fed from one core to another. The shunt windings have diodes and resistor-capacitor (RC) integrating networks injected in between cores to also produce a 6 to 1 stepdown in frequency. One of the four windings is used as output to feed a unidirectional pulse through a diode to the SCR gate. If the first pulse at terminal 1, 2, is fed to the first SCR, CR27, the next pulse at terminal 7, 8, would be used to feed the gate of CR28 to obtain 180 degree phase shift necessary for push-pull operation to produce Phase A output. Using the same technique of pulse selection, the output for Phase B and Phase C is generated resulting in a 3-phase 400-cycle output with push-pull operation 120 degrees apart.

From the previous explanation, it follows that the input power circuit is 2400 cycle ripple, not 400 cycle. The ripple has an amplitude of 1 to 2 volts across a battery impedance of 0.04 ohms. This produces a peak power radiation of 25 to 50 watts with strong harmonics in the 35 kilocycle region due to ringing of the input filter which produces only 3 deci bels of attenuation. It is obvious that the filter is not very effective and is being redesigned. By proper dressing of leads and shielding critical wires in the missile distribution system, the effects of radiofrequency interference have been minimized.

The output of the inverter is a smooth sine wave with less than 4 percent distortion. The voltage regulation is ± 1.5 percent from no load to half load and ± 1 percent from half load to full load. The frequency is merely specified at ± 0.5 percent accuracy and stability at present. In actual practice, ± 0.05 percent is maintained since a ± 0.002 percent crystal is used. In the new specification, ± 0.5 percent accuracy and ± 0.1 percent stability for 12 hours is specified to meet the requirements of the guidance system.

The rated output of the inverter is 115 volts, 400 cycles, 3-phase, Wye connected, 650 volt-amperes, with a 200 percent overload capability for 60 seconds. The present missile load is 500 watts maximum.

This completes the technical resume of the inverter. The method of handling a product improvement program by the Lewis Research Center will be given using the inverter as an example.

Background

When the Centaur program was transferred to Lewis in October, 1962, the ~~static inverter~~ was a critical, unreliable item and a general lack of understanding existed about its operation, usage and internal safety margins. Since then, the component has passed design proof-tests and extended time testing, and has reached a mean time between failures (MTBF) of 50,000 hours under laboratory conditions.

A list of problems encountered and their solutions:

Problem 1:

The original 25-pound inverter was overloaded, being rated for only 300 volt amperes, while the load was and is 500 voltamperes. In addition the original configuration employed ac transfer resulting in switching discontinuities.

Solution:

The problem was recognized, a 650 voltampere inverter, weighing 35 pounds, was ordered and eliminated the ac switching. This is between what we call F-1 and AC-2. F-1 is the one that blew up at the pad. That happened before Centaur was transferred to Lewis, incidentally.

Problem 2:

The new inverter was purchased as a "Black Box" to a set of input-output specifications without due regard for internal safety margins or adequacy of circuit design details, as well as correct usage. This was mentioned earlier in explaining the schematic.

Examples:

- a. Overload circuit bypass.
- b. Failure to recognize critical importance of input impedance or switching procedure.
- c. Failure to recognize critical internal transients.
- d. History of insufficient tests and inadequate documentation.

Solution:

The Centaur Project Office assigned a circuit specialist to analyze the problem in all its aspects and to implement corrective measures. Initially the following specific steps were taken:

- a. Issuance of Technical Directives Nos. 50 and 75 instructing the contractor to make certain parametric measurements, not recognized in the specifications, namely the effect of low input voltage and high input impedance as manifested at Atlantic Missile Range. Prior to launch the inverter works off of ground support equipment (GSE) ground supply and is a rectifier power supply. This requires a cable run of 350 feet from the blockhouse up to the tower to the vehicle. If you will recall the schematic, there is a series resonant charging circuit in the input. Although it is a push-pull parallel SCR, commutating capacity circuit, series inductive effects in the line enter the picture and caused what we call multiple starts.

If the time sequences are not correct at inverter start, the overload circuit will kick out and the inverter cycles again until it does. It has been found that the line impedance entered into this, the resistance as well as the inductance. Actual measured values of resistance and inductance were made before the inverter failed to commute completely. This is the effect that had to be cleaned up at AMR. A new run had to be made using heavier wire. This could not be a coaxial run because there were too many power takeoffs in the tower.

- b. Lewis procurement of an inverter and initiation of comprehensive laboratory testing and analysis program for correct evaluation and understanding of the component. Subsequently the contractor embarked upon a similar program.
- c. Detailed followup by the Project Office of all failures and corrections, in close cooperation with General Dynamics Corporation and the vendor. Lewis had the task of going to Borg-Warner and recommending inverter changes. Lewis had to go down to the parts level, and parts application requirements, to correct the situation.

Stimulation of the contractor's engineering staff to concentrate on the inverter and undertake in-house circuit analysis and laboratory program.

Following is a list of reliability improvements made to date:

1. Improved low voltage performance and eliminated noise and transient susceptibilities by changing regulation circuit for oscillator and countdown circuitry.

Recalling the schematic in figure 3 the regulation circuit controls the crystal oscillator. There is a Zener diode regulator in that supply. The Zener diode was well within its power rating, namely, 0.5 watt, at 22 volts. The inverter is designed to operate, according to spec., from 25 to 30 volts. Load transients were recorded at the Cape prior to launch which dropped the supply to 22 volts even for milliseconds. This was enough to decommutate the inverter. An 18 volt, 10 watt, Zener diode was used to regulate the oscillator circuit. This removed the noise susceptibility completely because the dynamic impedance with the 10 watt Zener diode was 2 or 3 ohms against 25 ohms with the 0.5 watt Zener diode.

Another thing found was that the 0.5 watt Zener diode and 26 volts battery supply produced a peculiarity which showed up as noise modulation again. It was in the regulation characteristic of the Zener diode. All this was eliminated with proper regulation circuitry redesign.

2. Redesigned the SCR core driver to eliminate false triggering or double pulsing in the memory core shift register. Remembering the shift register, which is driven with the SCR, produces 6 output pulses, sometimes a second pulse is obtained immediately after the first one. This was eliminated by putting a small resistor in the SCR core driver anode circuit.

3. Replacement of misapplied capacitors with high reliability (Hi-Rel) type in the shift register.

4. Elimination of certain high vibrational stresses. This happened prior to AC-2 launch. Lewis had the responsibility to declare the inverter flight-qualified upon the completion of two inverters through design proof testing (DPT), and extended time test (ETT), a watered-down extended time qualification of the DPT. The qualification time was 15,000 hours. It was decided to qualify them at 5:00 o'clock in the afternoon when 15,000 hours of operation would be reached. This was 3:00 o'clock in the afternoon. A half-hour later one of the inverters failed. Fortunately it was in the third vibrational cycle. It was found that the main ground strap from the input connector to the transformer strap, which carried all the battery current, had broken due to lack of proper stress relief. It was a large conductor made of double zero wire. Lewis immediately declared a flight constraint, removed the inverter from the vehicle, put a longer wire on, retrofitted all the other inverters. Lewis has not had a failure on the inverters since. That was the last deliberate malfunction on the inverters. The others have been human causes.

5. New parts layout with improved cable harnesses (This occurred between the first 650 voltampere inverters, of the -1 series, and second major improvement of the -3 series).

6. Imposition of NASA soldering specification, 158B.

7. Improved reflective and radiative coating (the white paint mentioned earlier)

8. Elimination of the overload bypass

Further planned improvements:

As of 2 weeks ago, an order for eight new inverters was placed incorporating the following improvements:

1. Thermal redesign

2. Addition of saturable reactors. A 0.1-microsecond 250-volt turnoff pulse was found in the main SCR circuits. It was due to the turnoff current in the one fired SCR forcing its way back through the other turned-off SCR. It developed a 250-volt spike on a 200 volt peak inverse voltage (PIV)-SCR. The first thing to do was to put a saturable reactor in to eliminate the voltage spike. Later it was decided to redress the leads and go to 250 volt SCR because the spike varied in amplitude from one inverter to another.

3. Replacement of lossy commutating capacitors with higher-reliability low-loss types. At present we are using 32 microfarad capacitors on the primary and 8 microfarad capacitors on the secondary. These are metalized capacitors. It is the only unreliable part left in the inverter. We have had no failure on that part to date for some unknown reason. In spite of this we are specifying polycarbonate capacitors which are being tested by General Dynamics Corporation now for qualification in the new inverters.

4. Thermally compensated countdown circuit Lewis checked the unijunction countdown circuits and found that they were not thermally compensated. All that was needed was a 50-ohm resistance in the unijunction base one circuit and they will operate from -55° C to 85° C with less than 0.5 percent frequency drift. The manufacturer had trouble thermally compensating it because of the coupling requirements. Therefore, the unijunction circuits will be tested up to 190° F before incorporation in each inverter.

5. Use of Hi-Rel parts throughout Lewis specified Minuteman quality or better for the new parts of new inverters on order.

6. Use of new high-temperature SCR's. We are using at the present time 2N685 made by General Electric or Texas Instruments. New SCR's will be 2N686 with a qualification up to 150° C for proper operation.

7. Improved regulation circuit with one of increased efficiency by reducing the overload capacity of the inverter since the present capacity is not needed. It will be reduced from 200 percent to 125 percent, which will still leave a capability of over 850 watts. This will improve the

efficiency another 10 percent from the present 65 percent. If we can get it up to 75 percent we might not need forced cooling. The efficiency limit for SCR inverters has been reached with the present design.

As a result of this program, the inverter is no longer on the critical list. So far, it is turning out to be a reliable inverter. I say this because I was trying to get a transistorized inverter. The more reliable this inverter is, the more difficulty I will have.

There is one other thing being tested at Lewis right now. The SCR's are mounted on an aluminum heat sink with a 2 mil micawasher on one side and a Teflon washer on the other to give it mechanical stress relief. This produces a temperature difference of 20° F, according to the manufacturer, between the SCR and the heat sink. We measure from 30° to 50° F. This is another source of operational limitation, namely, the upper temperature limit of the inverter, which is limited again by the SCR heat rise.

We are using, at present, beryllium-oxide washers in our tests. Beryllium-oxide washers, in case you are not familiar with them, are made by Brush Beryllium Company and have a thermal conductivity better than pure aluminum. It is a perfect electrical insulator and is a white ceramic. Basically, it has the mechanical properties of a ceramic. It has been known in the field for a couple of years, but it has never been tried in the inverter. We have used it, and specified it for the guidance system in several areas, with good success. That is, when used in conjunction with a silver shim. The silver shim is used to fill the pores of the beryllium oxide and to take up the slack of non-parallelism between the beryllium oxide washer and the mounting surface. The 2-mil soft-silver shim will squeeze out and fill the voids and prevent cracking of the beryllium oxide washer. The beryllium oxide has a tensile strength, in two grades, one at 25,000 psi, and the other 35,000 psi.

The new inverters are being ordered to a voltage accuracy and stability of ± 1 percent. The accuracy is defined at ± 1 percent, but the stability is defined as ± 1 percent for a 12-hour period. The frequency is ± 0.1 percent, both in accuracy and stability for a 12-hour period.

We are also in the process of evaluating the transistorized inverter from three sources, as a backup, and in all three cases the efficiency is about 10 percent better. In other words, it will approach 85 percent. If it averages 80, we will be happy because forced-air cooling will not be needed.

Power Distribution Problems

In the area of power distribution, the biggest problem is transients. The problem of AMR line impedance from GSE prior to launch was mentioned earlier.

Another problem was the telemetry filter used to protect the telemetry power supply from the GSE. The telemetry system was energized

from the ground power supply prior to launch. It worked fine on the vehicle and on the battery but when it was operated from the ground, the telemetry power-supply transistors were destroyed. It turns out that energizing and de-energizing the ground support equipment turned off the toggle switch and left a bank of 4000 microfarad capacitors on the telemetry power supply, which put a reverse voltage, the full 28 volts on a $1\frac{1}{2}$ -volt base to emitter power transistor. The rest is history. We cured that by putting a diode filter, and it is literally a diode filter because there is inductance and capacitance in the filter to suppress some other radio frequency transient radiation into the telemetry system itself from other sources.

Another source of transients in the distribution system was random firing of SCR's due to transients in the order of microwatts, running up and down the signal cables and the power distribution cables on the vehicle. The cure for that was a diode across all relay coils within the case of the relay itself. The relays are enclosed in steel cases where ever possible.

All switched inductors must have diodes directly across the inductors, plus shielded leads for critical lines.

There are several SCR's used for program switching, and this has played havoc with us, random vernier engine turn-on, programmers being programmed improperly, and so on. We eliminated most of these problems by minimizing the transients to a tolerable level, and further work is being done to minimize it even further.

Pyrotechnique problems: The squibs are electrical detonators for the explosives, in nose fairing and the insulation panels that have to be jettisoned during flight. When the squibs are fired, they can statistically produce an open circuit or short circuit. If they produce a short circuit they will destroy the battery. This condition was corrected by using a thermal latching relay that acts in the order of 2 milliseconds. Once a squib is energized, the heavy current activates the thermal relay and opens the circuit, and protects the battery.

In the area of the guidance package, we have the computer which can scramble in 4 milliseconds if the power is interrupted. We have no simple solution at the present time. At the time the guidance package was designed, the power-supply time constant should have been made at least 25 milliseconds, just from rule-of-thumb engineering. Instead, it is 4 milliseconds.

We have looked into the solution of using a battery, shunted across the guidance power supply in case of power failure, but it was too bulky a solution, particularly for the computer. Since the rest of the system was no better off, we decided that this was not feasible at all.

Lewis is now in the process of redesigning the guidance power supplies for a higher time constant and reducing the sampling-rate time constant of the inverter from 200 milliseconds down to at least 50 milliseconds so that if the inverter kicks out, it will come back on during the energy storage time of the power supplies in the guidance package.

A recent problem occurred on AC-4, we are flying what is called closed loop. The Centaur guidance system will now direct Atlas-Centaur instead of being programmed. That means it will also feed information down to the Atlas autopilot for use, which required a signal line running up from Atlas to Centaur to close the loop. The autopilot servo amp was reacting to false signals. This turned out to be a beat note between the Atlas 400 cycle supply and the Centaur 400 cycle supply, and was being produced on the 28 volt battery line which has a low impedance. A heavy filter had to be placed in the servoamp supply line to correct the ripple to a tolerable level. Another change was made to improve performance. The frequency of the Atlas inverter was changed 2 cycles. It is a rotary inverter and the frequency can be shifted a little better than the static inverter on the Centaur, which is crystal controlled. By shifting it 2 cycles, the beat note does not enter the tuned filter in the servoamp loop.

This concludes a brief summary on the Centaur electrical problems and how they were solved.

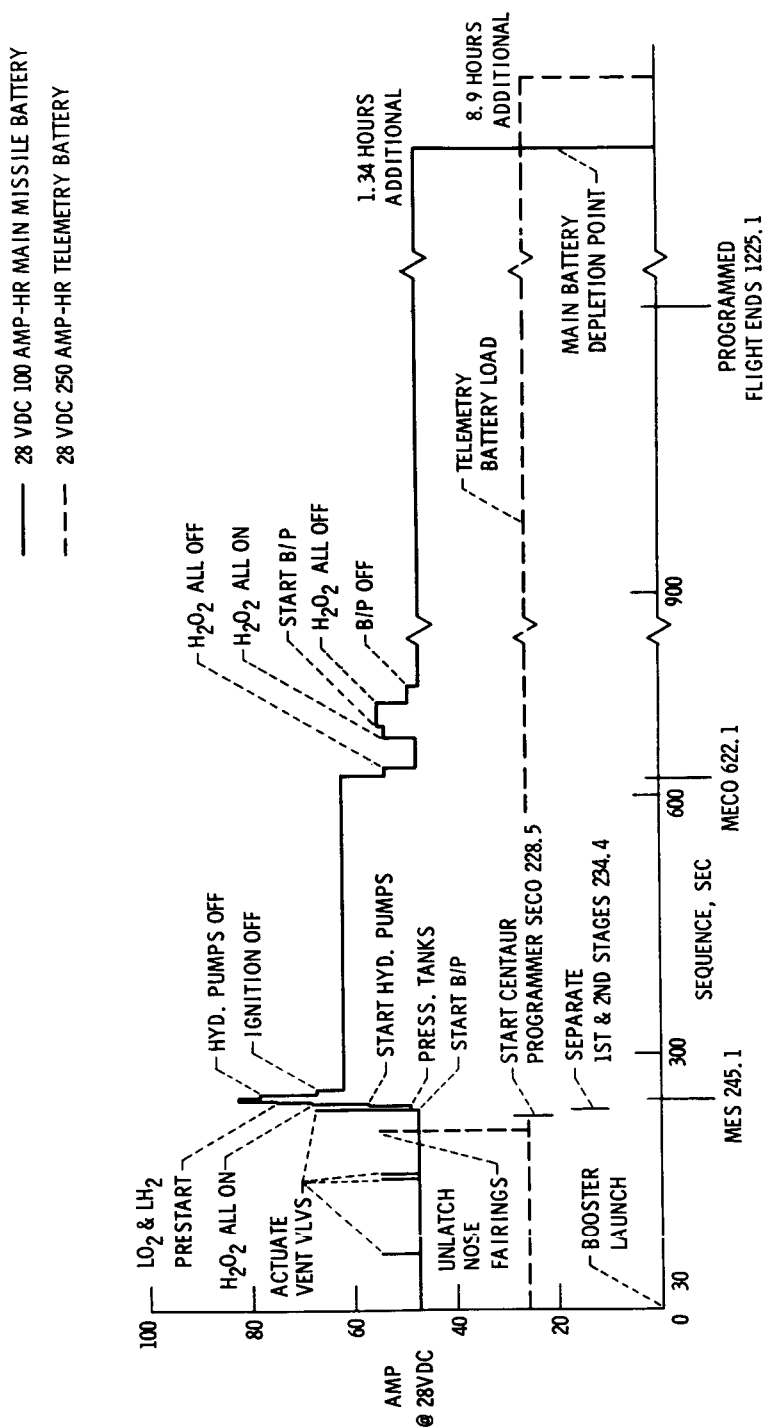


Figure 1. - AC-3 Battery current load profile.



Figure 2. - Top view of inverter.

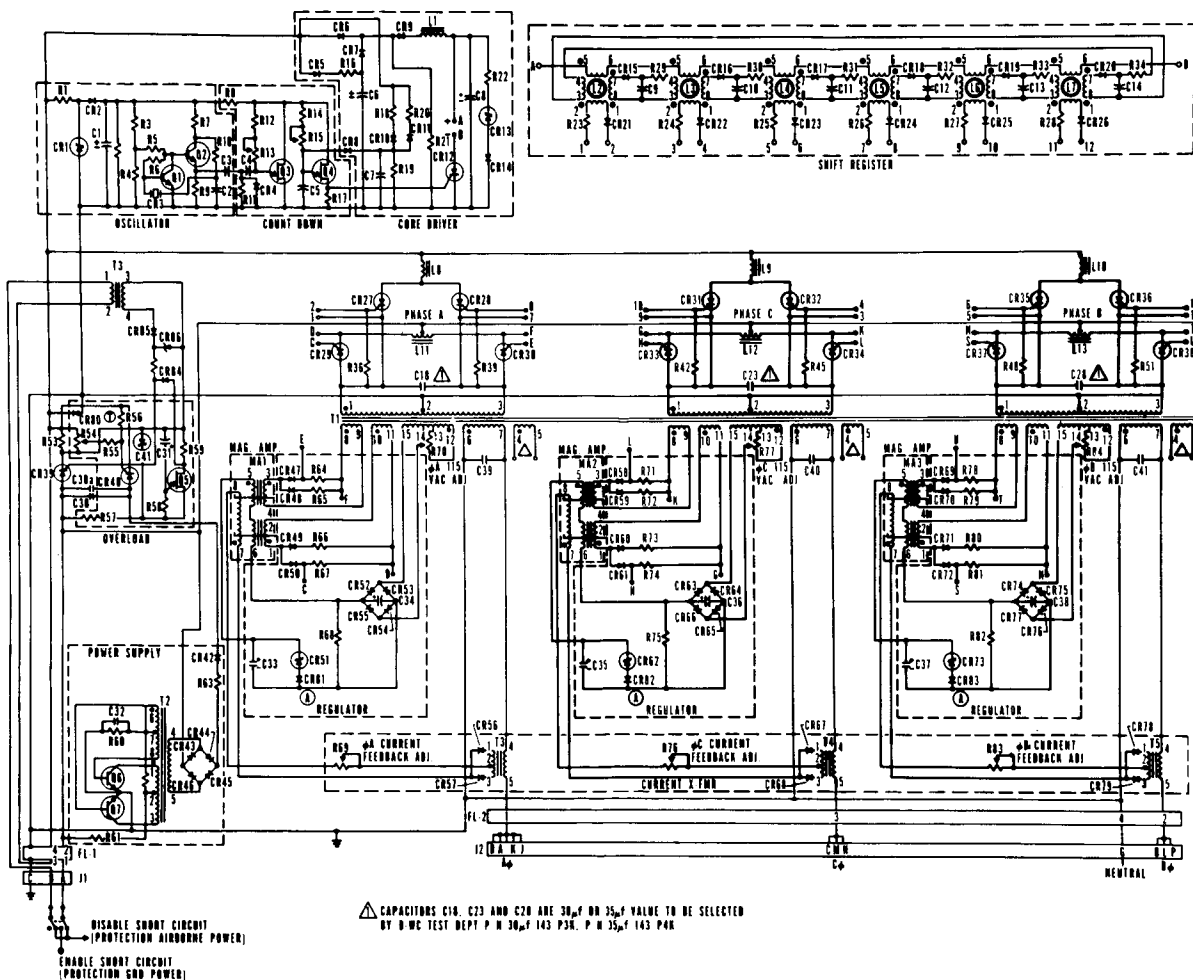


Figure 3. - Inverter block diagram and schematic.